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Nonlinear Dynamics of Shape Memory Alloys Actuated Bistable Beams

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Abstract: The phenomenon of bi-stable behaviour has been widely used in the structural design, as it can provide large deformation by switching between two stable equilibrium positions. This paper aims to investigate the intrinsic nonlinear dynamic characteristics of an actively controlled bistable beam using a simplified spring-mass model. The dynamic model for an active (heated) SMA wire driven bistable beam is established based on a polynomial constitutive equation to describe the thermomechanical behaviour of the shape memory alloy. The actively controlled bistable beams are designed, fabricated and experimentally tested to achieve the morphing behaviour snapping-through from one position to another. The results obtained from the experimental testing and the theoretical simulation are compared to validate the proposed model. Dynamic behavior of the proposed SMA wires actuated bistable beam under varying external excitation is investigated to show the influence of the thermomechanical loadings. Analysis of the experimental data and simulation results shows that the SMA wires actuated bistable structure can be well-performed for the bistable switching. It also approved that the different behaviours of the system, including periodic responses, complex responses and chaos can be accurately predicted using the proposed simplified model.

Keywords: Bistable structures; shape memory alloys; nonlinear dynamics.

1. Introduction

There are many physical examples in the natural world exhibit multiple stable characteristics, such as the Venus flytrap, plant leaves and seedpods [1–3]. In recent years, this multi-stable structural phenomenon has attracted considerable research interests in developing advanced structures with smart functionality, in particular for the engineering applications in energy harvesting and morphing aircrafts [4–12]. The multi-stable structures with the capacity of shape-changing can receive many engineering applications in the Aerospace, Energy and Marine industrial sectors, where always demand the structures can transit between two or more stable positions for achieving benign performance with respect to the varying surrounding circumstances. Moreover, another outstanding feature of multi-stable structures is that neither any power nor any locking mechanisms are required to enable them to remain in stable positions.

A bistable beam is one of the simplest forms that are widely used to construct multistable mechanical structures. Moreover, the nonlinearity of its structural and dynamic behaviour can be exploited for broad engineering applications. Pontecorvo et al. [9] applied a series of bistable arches to design a multistable cellular honeycomb-like structure, which is able to undergo large deformations for the chord extension morphing application of a helicopter rotor. Both numerical simulation and experimental setup have been carried out in their work [9] to demonstrate the bistable beams in morphing applications. A centrifugally actuated von Mises truss has also been designed to implement the passive chord morphing mechanism for helicopter rotor blades in Moser et al.'s work [10]. Moreover, the multistable morphing structures provide promising design solutions for micro-actuators and optical switching in MEMS devices. Liu et al. [13] designed a micro-actuator device with two rows of bistable micro-actuators, which are formed by antagonistic pre-shaped double beams. Brenner et al. [14] proposed an optimal design of this type bistable switch that possesses a better force-displacement characteristic. The multistable morphing structures have also attracted considerable research interests and broad applications in energy harvesting and energy dissipation [4,5,15–17]. For example, a piezoelectric energy harvester was designed by utilising the snap-through motions from the bistable behavior to produce electrical power under low-frequency excitations [5,15]. Many other research efforts that take advantages of the multistable structures have been made for vibrations absorption [16,17]. A single degree-of-freedom mass-spring is designed as a bistable system, which is used to study the problem of forced oscillations absorption [16]. A more practical model formed by von-Mises truss is introduced to analyse the dissipation properties and examine the energy absorption of a bistable system [17].

Moreover, different scales devices and structures have been investigated to demonstrate the practical applications of utilising the nonlinear dynamical characteristics of a bistable system. Sulfridge *et al.* presented a nonlinear dynamics analysis for a bistable MEMS – a buckled micromechanical beam that was switched from one stable state to the other by the radiation pressure [18]. Their nonlinear dynamic model predicts that the buckled beam can be toggled by a transverse force, which is slightly higher than

the toggling threshold force. This work sheds lights on the rich dynamics of micro-mechanical bistable systems for the application in switching. Krylov *et al.* investigated another pre-buckled electrostatically actuated beam for the feasibility of two-directional switching by fringing electrostatic fields [19]. The general results presented in their work shed lights on the intrinsic nonlinearities of micro-devices on the structural stability, which can be exploited by designers in MEMS/NEMS based applications, e.g. electromechanical switches, biosensors etc. Aimmanee *et al.* studied the snap-through buckling behaviour of a buckled beam bonded with segmented piezoelectric actuators using a mathematical model, and validated the theoretical predictions with experiments [20]. Different with these static switching strategies, Casals-Terré *et al.* proposed a dynamic snapping strategy that can switch between states of a bistable mechanism utilizing mechanical resonance phenomenon [21]. They demonstrated that if a bistable structure is driven into a resonance near one of its stable states, a sufficiently large amplitude of vibration may be achieved to switch between its stable states [21].

In recent years, smart materials were always applied to implement the actuation mechanism for the transition capability of multi-stable structures. The internal properties of these smart materials can be changed under external stimuli, such as stress, temperature, electric or magnetic fields. Therefore, they are ideally used for implementing the smart functionalities of multi-stable structures [22]. Shape memory alloy (SMA) which is a typical smart material possesses the properties of shape memory effect (SME) and pseudoelasticity [23]. As such, the SMA wire had been widely used to control structural behaviour [24,25], for example the flexible biomimetic fin [26] and tentacles [27] in the bionic applications. The dynamic characteristics of SMA based structural systems have been studied to possess specific properties [28,29], for example, Boeing has developed an active serrated aerodynamic device with SMA, which has been proven to be very effective in reducing noise during take-off [30,31]. The dynamic characteristics of a planar bending actuator embedded with a shape memory alloy (SMA) have been investigated to accurately predict the deflection process [32]. The planar bending actuator is constructed by an elastic substrate and an embedded SMA wire. This type of planar actuator is able to generate relatively large stress and strain through stimulating the SMA wires [32]. Therefore, SMA actuated structures have been widely employed in the temperature-dependent applications. For example, a SMA-pendulum system and an adaptive origami-stent system are proposed to present temperature-dependent behaviour of the SMA and the possibility of thermal control of the system [33]. Temperature variations can be employed to change either the position (static) or the response (dynamic) of a SMA based system in a variety of ways. The creation or suppression of chaos and the orbit changes can be analysed by actuating SMA [33,34].

In this paper, the near-equiatomic NiTi alloy wires are utilised to drive a bistable beam, actively. A simplified analytical model is then developed to study the nonlinear dynamics of SMA wires actuated bistable beams. The capability of applying SMA wires to influence the dynamical characteristics of the bistable system is, for the first time, investigated. It is worth to mention that the response of SMA wire

actuators is too slow to be applied for the vibration control, but the thermomechanical property of SMA wires can be utilised to affect the dynamic characteristics of the system. For example, a bi-stable von-Mises truss (VMT) integrated with SMA wires to provide the actuation force for the transition of the VMT between two stable equilibrium conditions [35]. SMA wires have been designed to column joint with a beam towards the stiffness and energy dissipative ability [36]. Moreover, SMA wires are designed as a suspension to support a rotor-bearing test rig to reduce the vibration level of rotating systems [37]. In addition, SMA wires have been widely used in the construction of morphing structures, for example, the SMA wires were designed to be attached to the hexa-pivotal joint to produce a shape morphing hinged truss structures [38]. In this paper, the SMA wires are designed built-in pin-joints on the beam, which is different with the previous work that embedded the SMA wires in the structure [32]. Because the embedded SMA wire structure is limited by the substrate dimension, and therefore cannot provide a better contribution of SMAs in many cases. The bistable beam is firstly simplified to a single-DOF lumped model in Section 2.1 without considering SMA wires, and the nonlinear behaviour of bistable beams is investigated with respect to different key parameters, such as stiffness and clamp distance. In spite of its simplicity, such a mathematical model is able to capture the fundamental dynamic characteristics of a bistable beam due to its nonlinearity and instability. Then, a polynomial constitutive model of SMA is established to model the thermomechanical response for the SMA wires actuated bistable beam in Section 2.2. Numerical results are obtained to analyse the switch phenomenon of SMA actuated bistable beams in Section 3.1. The study of nonlinear dynamics of bistable beams was originally inspired from the investigation of an auxetic structure, as shown in Fig. 1. The bistable beam has the ability to snap from one stable state to the other when excited with sufficient input actuation, as such, different displacements can be achieved for this type of the auxetic structure by actuating separate bistable beams. Therefore, a bistable beam with SMA wires as the actuators is proposed as a typical bistable structural element for this auxetic system. Furthermore, Section 3.2 illustrates an experimental rig that is designed for testing the stress-strain-temperature relationships of Shape Memory Alloys in a practical SMA wires actuated bistable beam. Since the structures are considered to work under diverse situations, the nonlinear dynamic behaviour of this system under different external excitations is investigated in Section 4. Numerical simulations are carried out to demonstrate the variety of responses, and compare the differences between the structural system with and without SMA wires actuating. Therefore, the topic investigated here are of interest for future research and development of SMA actuated bistable beams.

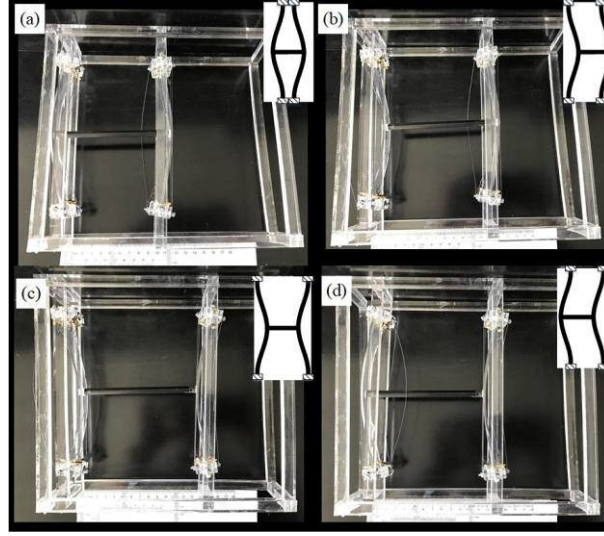


Figure 1. Top view of a laboratory-scale auxetic structure constructed by bistable beams.

2. Spring-mass model for a continuous buckled beam

2.1 Single mass problem

A representative model for the shape memory alloys actuated bistable beam is designed and illustrated in Fig. 2 (a). This representative beam model is fixed at both ends, and an axial force is then applied to produce buckling, as shown in Fig. 2(b). Both ends of pre-stretched (5%) SMA wires are fixed with built-in pin-joints on the beam, which can be actively heated by means of Joule effects with electrical currents. Through heating the SMA wires, the bistable beam can be actively actuated to reach another stable state.

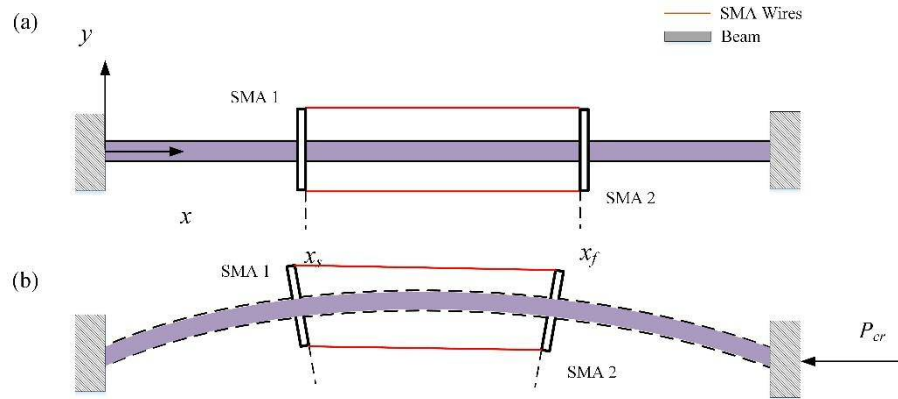


Figure 2. The shape memory alloys actuated beam model. (a) Undeformed beam. (b) Bistable beam.

In order to establish a simplified dynamic model for the shape memory alloys actuated bistable beams, as shown in Fig.3, the beam is firstly assumed to be modelled as a discrete structure with two linear springs clamped at both ends that are used to simulate the spring stiffness and torsional stiffness at the ends [4,39]. The mass is only allowed to move along the vertical direction with the displacement denoted by y , while the span distance of two clamped springs are x_v and x_f . Although the springs provide the

linear restoring resistance, the resulting entire system is highly nonlinear due to the geometric configuration. Therefore, this simplified system is defined by a dynamic model in the following form,

$$\frac{d^2w}{dt^2} + \frac{2kd}{\cos\theta}w = 0 \quad (1)$$

where w is the original length of the springs, m is the mass displacement, k is spring stiffness, κ is torsional spring stiffness and d is the half distance between the rigid supports. θ is the inclined angle along horizontal direction

$$\kappa = \frac{1}{2} \frac{dw}{d\theta} \quad (2)$$

and κ is defined as a linear relationship with w and a ratio α , given by

$$\kappa = \alpha w \quad (3)$$

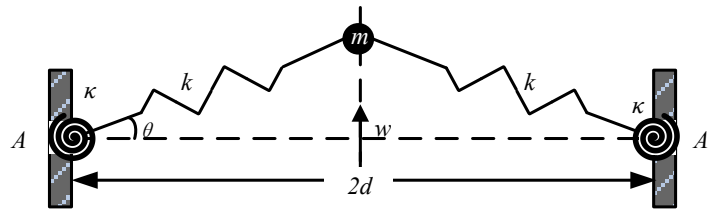


Figure 3. A simple representative buckled beam model, where a mass is supported by pairs of springs pinned to rigid supports.

The nonlinearity in Eq. (1) can provide some typical dynamical behaviour in the bistable model. The nonlinear behaviour of this spring-mass system is firstly studied without considering extra forces. Therefore, the system is considered to be conservative and its effective total potential energy U is given by the sum of its potential strain energy and its torsional energy

$$U = \frac{1}{2} \frac{2kd}{\cos\theta} w^2 + \frac{1}{2} \kappa \theta^2 \quad (4)$$

The effective potential energy U of the spring-mass model with $\alpha = 0.1$ is computed and shown in Fig. 4, in which the different torsional spring stiffness κ results in different dynamic characteristics of the system. Figure 4(a) shows that there are three stable states (local minimum stationary points) of the spring-mass system, but a different behaviour is occurred when the torsional stiffness κ is changed, as shown in Fig. 4b.

Then, in order to investigate the characteristics of the system with varying parameter κ , Eq. (1) is rewritten as

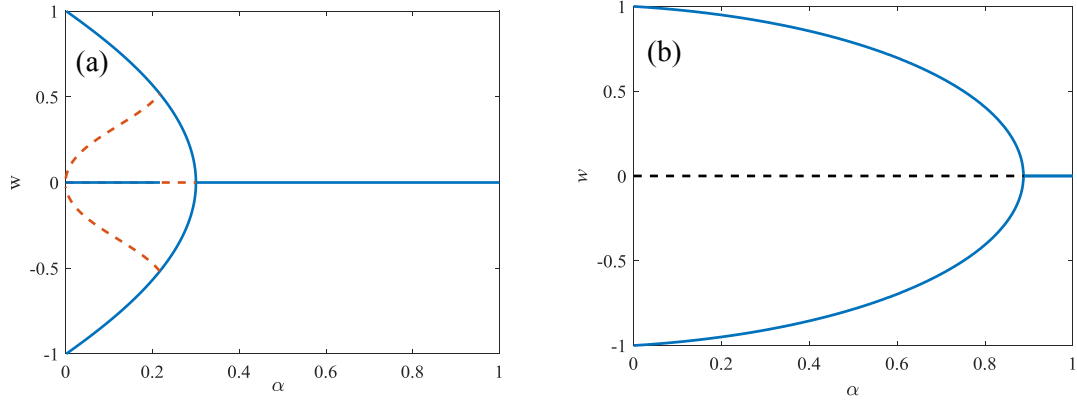


Figure 6. Bifurcation diagram for the spring-mass model with unit parameters. (a) $\gamma = 1$, $\beta = 1$. (b) $\gamma = 1$, $\beta = 0.1$.

2.2 Updated model of a SMA wires actuated bistable beam

However, for a realistic model dissipation must also be considered, the dynamics of the problem can therefore be extended by the addition of a linear dissipation parameterised by γ . Moreover, an external force induced by SMA wires is considered to construct an updated model for SMA wires actuated bistable beam, as illustrated in Fig. 7.

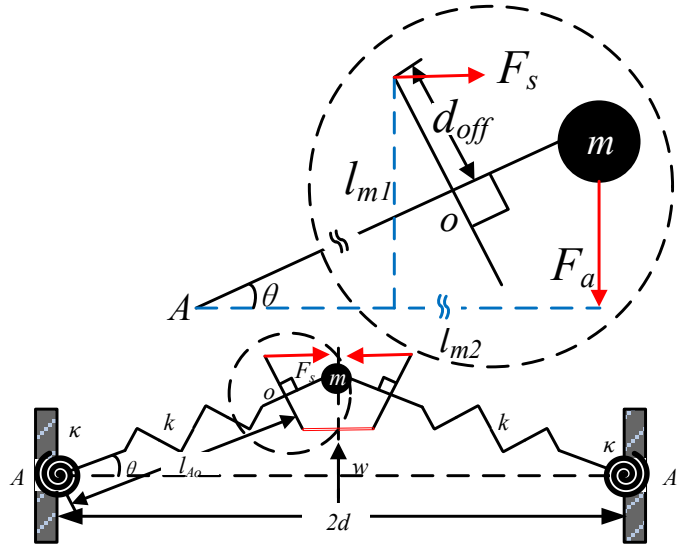


Figure 7. An updated model of a SMA wires actuated bistable beam.

Now, the problem can be fully defined as a standard dynamical system in the following form,

$$\ddot{w} + \gamma \dot{w} + \frac{1}{m} (F_s \cos \theta - F_a) = 0 \quad (6)$$

where γ is a linear viscous dissipation coefficient, and F_s is the actuating force provided by the SMA wires to stimulate the lumped mass. The detailed geometry relationships of the SMA wires actuated

bistable beam is shown in Fig. 7. The actuating force F is derived from the induced force F_{SMA} given by SMA wires

$$F = \frac{F_{SMA} l_{half}}{l_{om}} \quad (7)$$

where l_{half} is a given length between the end of the beam and the pin-joint of SMA wires. The force F_{SMA} induced by SMA wires is obtained from the SMA thermomechanical behaviour. The SMA thermomechanical behaviour is represented by a polynomial constitutive model that establishes a stress-strain-temperature (σ - ϵ - T) relation [34,40,41]. This constitutive model considers that the austenitic phase is stable at high temperatures, and two variants of the martensitic phase, induced by positive and negative stress fields, are stable at low temperatures.

$$(8)$$

where σ_0 , ϵ_0 and T_0 are material constants and T_0 is the temperature below which the martensitic phase is stable. Assuming that T_0 is the temperature above which the austenitic phase is stable, it is possible to write the following relationship: The force-displacement-temperature curve, therefore, is obtained using the following equation,

$$F = \frac{A_{SMA} E_{SMA} (T - T_0)}{l_{om}} \quad (9)$$

where A_{SMA} is the cross-sectional area of SMA wires and l_{om} is the initial length of the pre-stretched SMA wire. Moreover, the length l_{om} of the SMA wire is varying with respect to different geometry configurations of the beam, as shown in Fig. 8. It is finally solved by

$$(10)$$

where l_{om} is the length between joint point and mass. Therefore, Eq. (10) is re-expressed as

$$l_{om} = \frac{F_{SMA} l_{half}}{F} \quad (11)$$

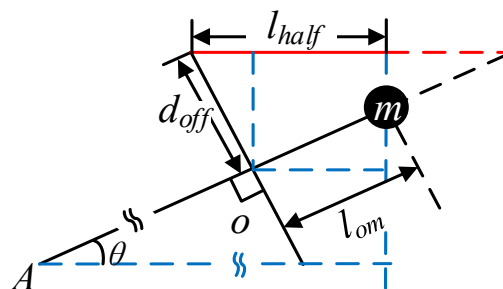


Figure 8. Actuating sketch.

Although the actuation of the beam is from SMA wires, the actuating force that stimulates the beam configuration to change (buckled up and buckled down) actually is F_a . The applied force F_s on the lumped mass defined in Eq. (7) is finally expressed as,

$$F_s = \frac{F_a}{\cos(\theta)} \quad (12)$$

Equation (12) presents that the applied force F_s is changing along with the time-varying parameter θ and the curve is plotted in Fig. 9. Moreover, it can be seen that the applied force F_s is approximately linear with the displacement w in Fig. 9, which is because of the small deflection that leads to a parametric linearization (i.e. $\cos(\theta) \approx 1$).

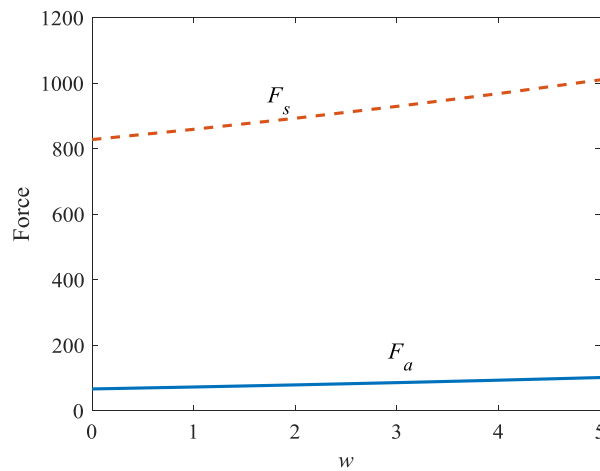


Figure 9. Force of the pre-tension (5%) SMA wire at supposed temperature 90 °C.

The NiTi wires with a composition of (Ni50.1Ti49.9 at.%) are used in this work and the thermo-mechanical properties of this material are listed in Table 1. Moreover, the temperature variation of SMA wires during transformation is tested by Differential Scanning Calorimeter (DSC). Differential scanning calorimeter (DSC) test, which reveals the heat flow verses temperature relationship of a material upon heating and/or cooling, is one of a few standard techniques to determine the transition temperatures of materials. Fig. 10 presents a typical DSC result of SMA in a heating/cooling cycle between -100 °C and 100 °C. As we can see, four different phase transition temperatures were identified using the tangent-lines method, as shown in Fig.10.

Table 1. Selected SMA materials properties.

Description	Value
Diameter, [mm]	0.5
Martensite Young modulus, [GPa]	22
Austenite Young modulus, [GPa]	50.3
Critical stress de-twinned martensite start [MPa]	100
Critical stress de-twinned martensite finish [MPa]	170
Thermal expansion coefficient [/°C]	1
Variation of austenite critical temperature with stress [MPa/°C]	3.5
Variation of martensite critical temperature with stress [MPa/°C]	10.2
Limit Strain [%]	7.2

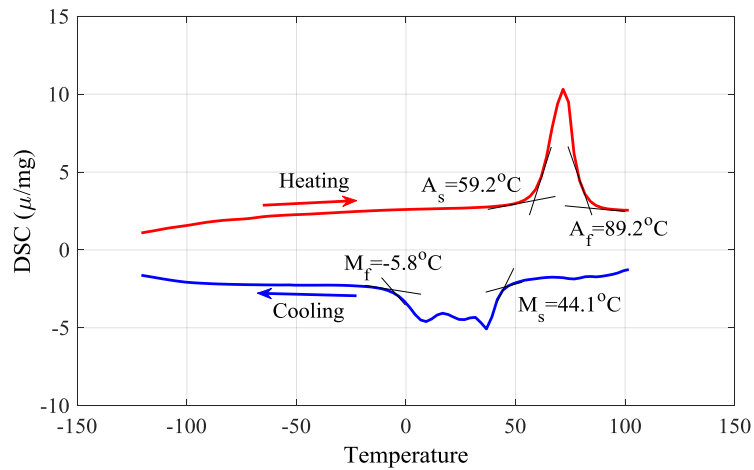


Figure 10. Measured DSC curves of SMA wires.

Finally, by substituting Eq. (12) into Eq. (6), the fully dynamic equation of this simplified spring-mass system is obtained with the relations of _____ , and expressed in Eq. (13)

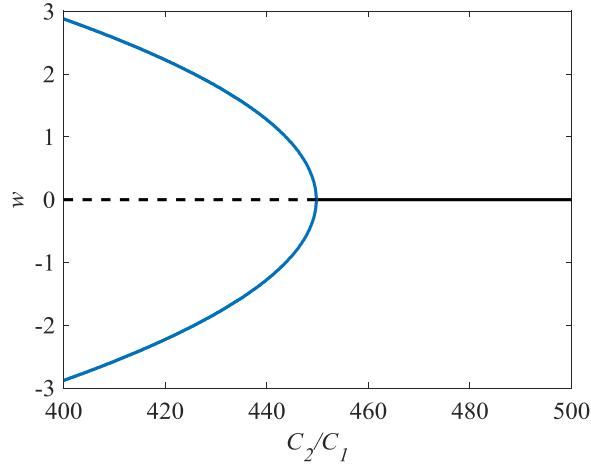


Figure 11. Bifurcation diagram for the updated model.

Subsequently, a slender beam was manufactured and compressed by the testing machine as shown in Fig. 12, in which the two bistable configurations were observed. The initial configuration of the beam at the first stable position is illustrated in Fig. 12(a). The buckled beam becomes unstable after applied voltage and finally snapped into the second stable position in Fig. 12(b). The first critical load and maximum deflection according to the experimental result are 60 and 2.3, respectively. The parameters and are defined as 35.7 and 420 for further investigation.

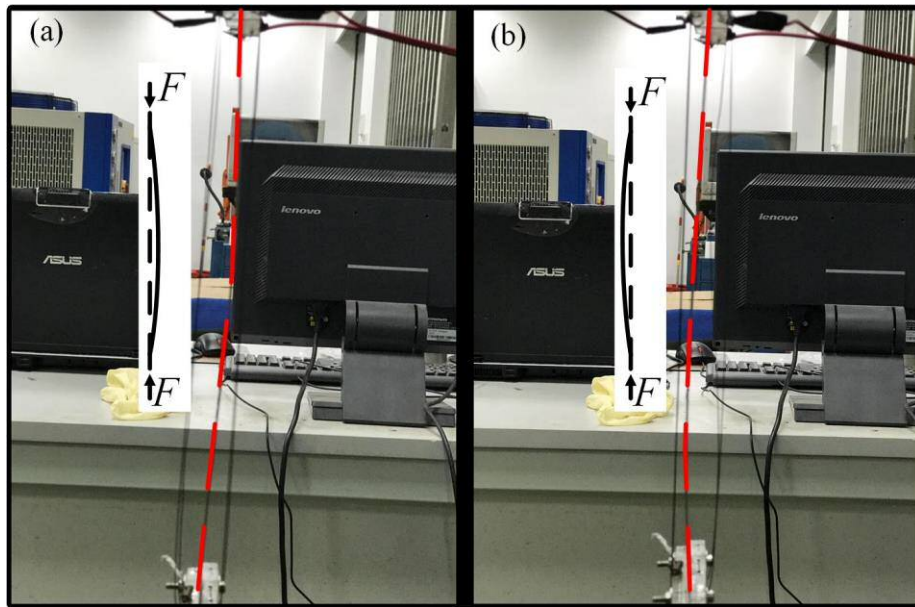


Figure 12. Photograph of the buckled beam. (a) First stable configuration. (b) Second stable configuration.

3. Numerical simulation and experimental validation

3.1 Numerical simulation

The governing equation for the motion of the SMA wires actuated bistable beam proposed in Eq. (13) is now used to study the nonlinear dynamic response of the system. The main parameters of the bistable beam are summarized in Table 2.

Table 2. Geometry property of the proposed beam.

Description	Value
Beam length, L , [mm]	500
Beam width, b , [mm]	30
Beam thickness, t , [mm]	1
Young modulus, E , [GPa]	206
Density, ρ , [kg/m ³]	8,050
Distance between supports, L_s , [mm]	499.7
Maximum displacement, w , [mm]	2.2
SMA wire length, L_w , [mm]	250
SMA wire diameter, d , [mm]	0.5
Offset distance, l , [mm]	10
Distance, l_s , [mm]	125
k_1 , [Pa/m]	$1.28 \cdot 10^9$
k_2 , [Pa]	$2.50 \cdot 10^{13}$
k_3 , [Pa]	$5.53 \cdot 10^{15}$

Few further simplifications had been made in the updated model for the simulation and design of SMA wires actuated bistable beams. To calculate the central force that actuates the system, the mass of total beam was assumed to be concentrated at its geometric centre. The nonlinear dynamic response of the bistable actuated by SMA wires is determined using Eq. (13), and the results are plotted in Fig. 13. The response is affected by the system (e.g. stiffness and the actuating temperature) and the dynamic response is shown under an actuating temperature of 90 °C. The bistable switching can be achieved depending on which of the two SMA springs (as shown in Fig. 2) is activated. Figure 14 shows that the presence of sudden jumps in the displacement of the beam is due to the snap-through motion and one SMA wire becomes slack and the other one is suddenly under tension. For example, if the initial configuration is the one shown in Fig. 2 (b), the SMA1 is activated to output the actuation force that drives the beam to the second stable state. When the switching process of the beam is finished, the SMA1 will become slack and SMA2 will be tensioned. During the switching process, both up (SMA1) and down (SMA2) SMA wires have nearly the same amount of strains and one is activated to stretch another one. It is obvious that such discontinuities cannot be eliminated and may be used to design a further close loop control system.

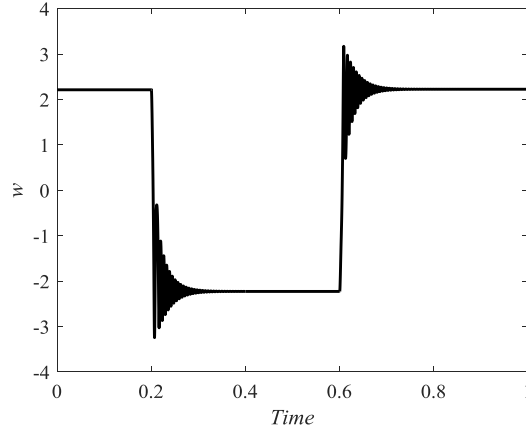


Figure 13. Simulation diagram for actuating bistable beam.

3.2 Experimental validation

An experimental testing for the proposed SMA wires actuated bistable beam was carried out to examine the effectiveness of the updated mathematical model. The main parameters of the beam and SMA wires are the same with the simulation used in Table 2. A contactless laser sensor (Keyence # LK-080) was installed side of the beam to measure the midpoint displacement directly. Figure 14 shows that the test rig was mounted to a material test machine and the clamped force can therefore be measured directly. The edges of the beam are clamped by two holders which are also capable for translating and rotating (Fig 2a), and the laser sensor is used to measure the middle displacement. Two separate electric circuits are connected to each side (up or down) of SMA wires and controlled by an external switch. Firstly, an initial compression (0.3) is applied to produce bistable configurations (Fig 2b). Next, one side of the SMA wires is heated to actuate the bistable beam switch to another bistable state. The displacement of the bistable beam is measured by the laser sensor. Subsequently, a similar operation is then carried out on the other side of the SMA wires for actuating the bistable beam to recover back to its initial state. Finally, the results are processed to obtain the nonlinear dynamic response of the bistable beam.

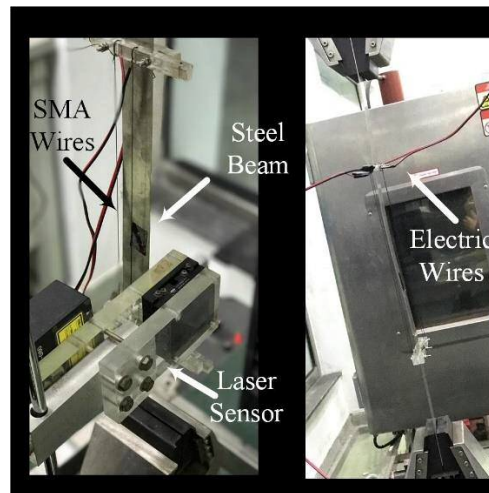


Figure 14. Photograph of the testing apparatus.

Figure 15 illustrates the experimental results of the dynamic response of the SMA actuated bistable beam. The measured displacement of the bistable beam is plotted as a function of time and successfully demonstrated the feasibility of this design by using SMA as an actuation scheme. From this figure, it can be seen that the experimental snap through motion can be successfully stimulated through charging one of the SMA wires (SMA 1 or SMA 2) (Fig. 15(a)). The beam then oscillates towards the targeted stable state, and the motion gradually decays due to damping (Fig. 15(b)). The black solid line shown in Fig. 15 (c) denotes the measured displacement curve for the beam, superimposed to the approximate prediction represented by the red dash line. This curve is corresponding to the first switching from convex configuration (2.2 mm) to concave configuration (-2.2 mm) indicated by the black box in Fig. 15(b) and the purely qualitative can be confirmed.

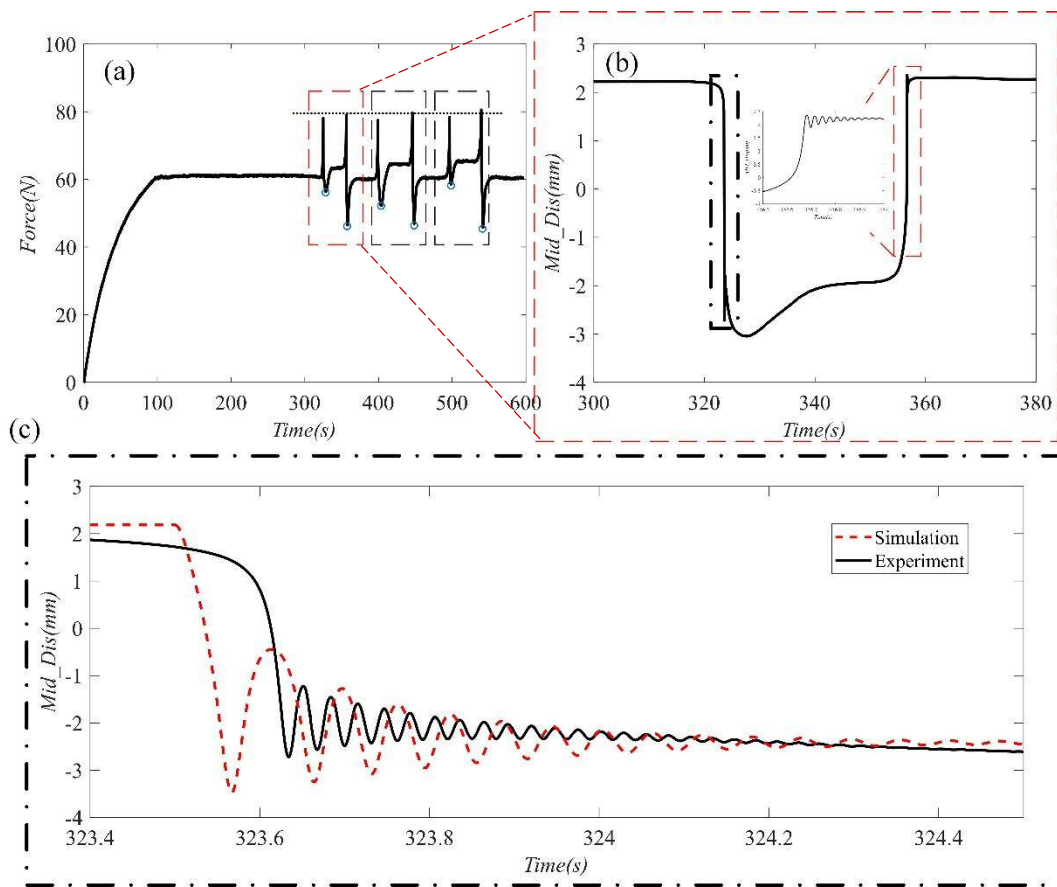


Figure 15. Experimental diagram for actuating bistable beam. (a) Force-time curve with 3 switching cycles. (b) Displacement-time curve in one switching process. (c) Comparison between simulation results and experimental results.

It is shown a good correlation between the analytical model (Fig. 13) and the experiments (Fig. 15) in terms of transition displacement of the SMA wires actuated bistable beam. The results obtained from the present mathematical model and experiment show a good agreement. This validation ensures the

accuracy and applicability of the developed model. The model is therefore approved to be able to accurately predict the nonlinear dynamic characteristics of SMA wires actuated bistable beams.

4. Dynamic behaviour and chaos

Since the bistable devices can be actuated using different switching strategies: statically or dynamically, it is useful to investigate the fundamental mechanism of a bistable system influenced by the external disturbance. For example, if the external disturbance is applied at a certain frequency, the switching to the second stable state can be achieved at a lower force. Therefore, it is of vital importance to study the nonlinear dynamical behaviour of SMA wires actuated bistable beams and the contribution of activated SMAs can be provided to toggle the beam in its stable states. The proposed model is used here by rewriting the governing equation Eq. (6) to include an external excitation force as follows

$$\frac{\text{---}}{\text{---}} \quad \text{---} \quad \text{---} \quad (16)$$

where $F \cos(\omega t)$ is a harmonic external force with amplitude F and frequency ω .

The influence of actuator temperature is firstly investigated for the free vibration system () under different cases of thermal loadings. Four cases are chosen here to provide general situations, which are system without SMA wire, temperature on 40 , 70 and 90 , respectively. Numerical simulation was carried out with different initial conditions to produce the corresponding nonlinear vibration responses of the system. The numerical results for the nonlinear dynamic responses of the system are presented in form of phase spaces in Fig. 16. Only one side of SMA wires (SMA1 or SMA 2) is considered to achieve one-way switch varying different cases. Figure 17 shows the phase space of the bistable beam with different temperatures induced SMA wires and without SMA wires, respectively.

The original system without SMA wires have three equilibria (shown as the black points in Fig. 16(a)), and the phase space diagram is also symmetric with respect to the vertical axis. It can be seen that two of the equilibria are stable, as same as the bifurcation diagram shown in Fig. 11. However, by considering the SMA wires with an initial temperature (40°C), the left stable equilibrium remains unchanged while the other stable equilibrium becomes smaller than before. The phase space of the system also becomes asymmetric, which means the position of the stable equilibria is changed. In other words, the shape of practical beam on two stable states will become inconsistent when one of the SMA wires is activated. Next, when the temperature is increased to (60°C), this characteristic becomes more obvious and it implies that the phase transformation of shape memory alloys has been induced (from martensite to austenite) . Finally, when the temperature increases to be above the austenite temperature (90°C), only one stable equilibrium exists. In other words, the SMA wires actuating beam will lost its original bistable feature when the stimulating temperature is larger than 90°C .

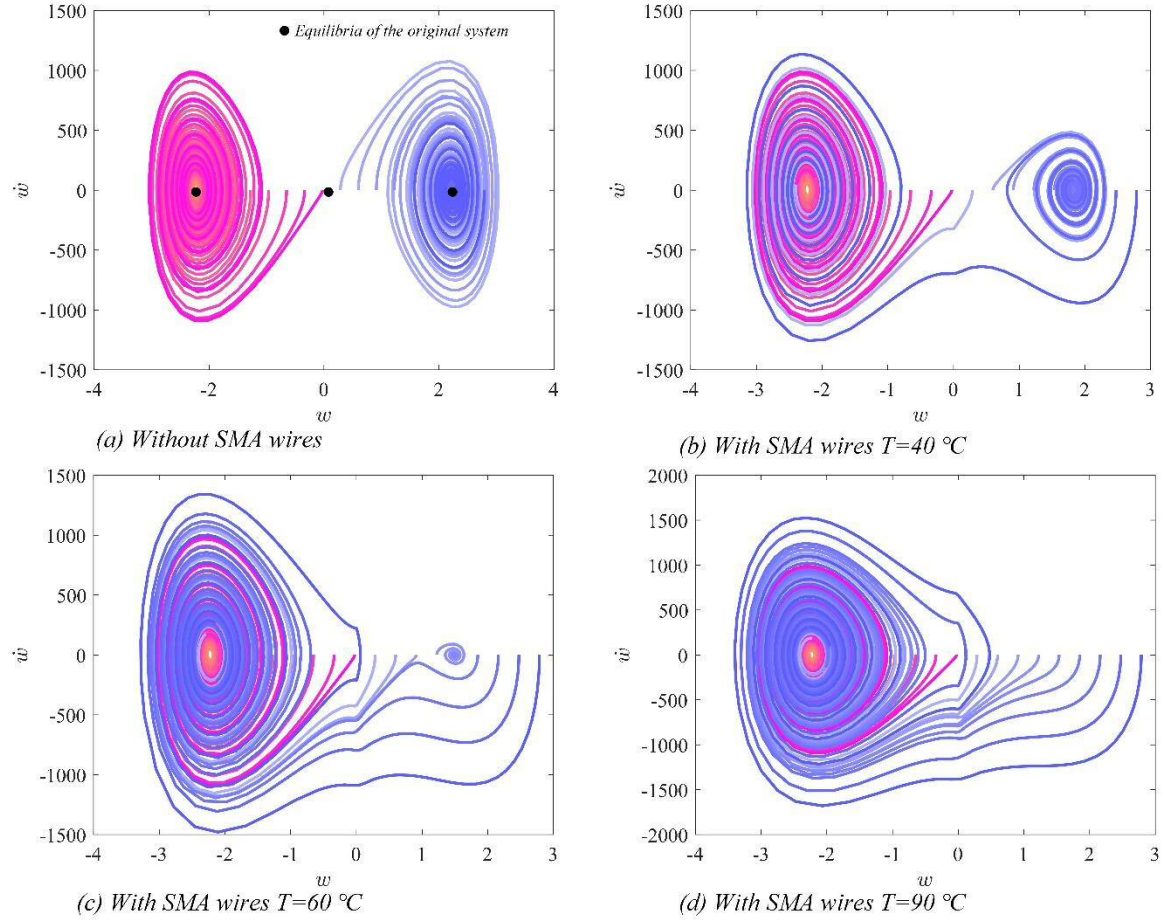


Figure 16. The bistable beam free vibration response at different temperatures. (a) Model without SMA wires.

(b) 40 °C. (c) 60 °C. (d) 90 °C.

The dynamical loading is now considered in the simulation of some operational conditions for the SMA wires actuated bistable beam using Eq. (16). It is assumed that the bistable beam is actuated by both sides of SMA wires (SMA1 and SMA2), which means that it can be switched between two stable configurations continually. The bistable actuating configurations are of concern with an actively control with a fixed temperature (90 °C). Firstly, the system is studied by considering bifurcation diagrams to provide a general understanding of the system dynamics. Fig. 17 presents two bifurcation diagrams showing the dynamic responses of the system when varying the amplitude or the frequency , respectively. It is noted that the change in both amplitude and frequency can cause significant different dynamic responses, for which both periodic and chaotic responses are possible. Figure 18 (a) shows the dynamic responses under varying excitation amplitude and a fixed frequency 100 Hz. It can be seen that for small force amplitudes, the system emerges a periodic response until $F = 490$ N, and afterwards the system exhibits a chaotic response until another period response appears. By increasing the amplitude, the system becomes chaotic except for few periodic region, such as $F = 940$ N. On the other hand, Fig. 17 (b) shows the system response under varying excitation frequency with a fixed

amplitude 300 N. It shows that, for low-frequency excitation, the system can maintain a periodic response (e.g. period-1 in 100 Hz and period-2 in 200 Hz). However, when the frequency reaches 700 Hz, the system emerges a chaotic response.

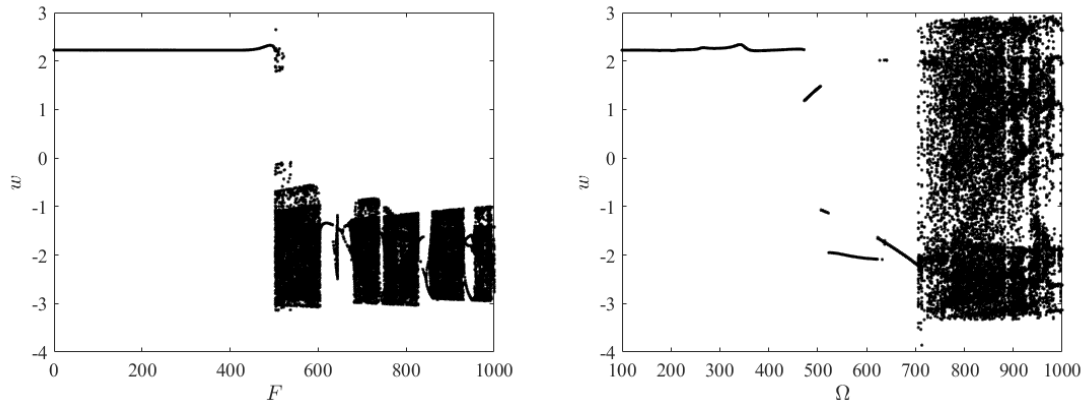


Figure 17. Bifurcation diagrams: (a) Varying excitation amplitude with a fixed frequency (100 Hz); (b) Varying excitation frequency with a fixed amplitude (300 N).

To further study the nonlinear dynamic response of the system, it is important to analyse both the phase space and Poincare section for some special cases. Fig. 18 shows the dynamic response of the bistable beam without SMA wires that are actuated under different loading conditions. Fig. 18 (a) - (d) present the system responses given by varying amplitude with the fixed frequency 100 Hz, which are related to the cases in Fig. 17 (a). Fig. 18 (d) - (i) are the system responses given by varying frequency with a fixed excitation amplitude 300 N, which are related to the cases in Fig. 17 (b). It was found that the amplitudes of used in all the cases are sufficiently large to produce bistable behaviour without the stimulation contribution from the SMA wires. Therefore, it is known that the cases (d), (e) and (f) are limited by the chosen value of frequency to achieve the bistable behaviour. Although different parameters may all generate chaotic responses (e.g. (b) and (h)), the characteristics of those responses are entirely different.

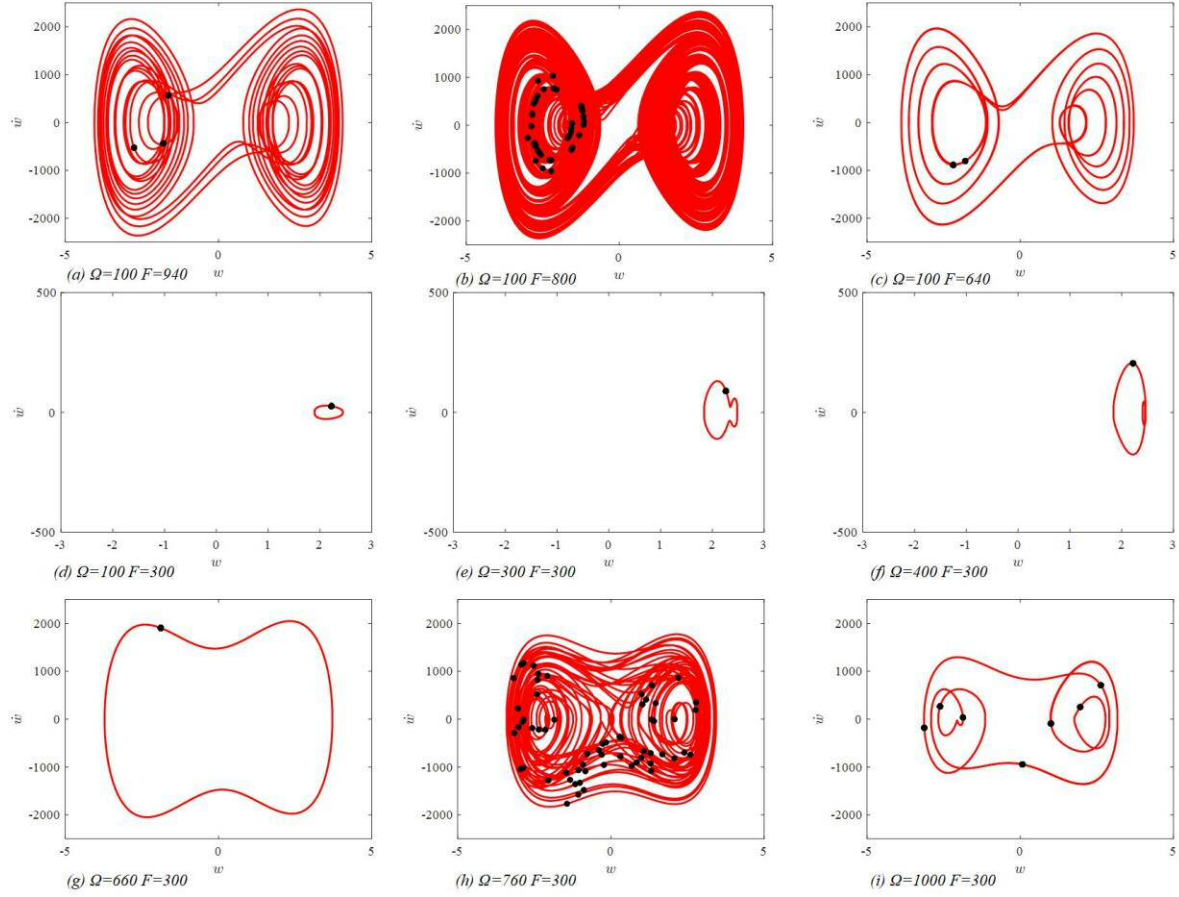


Figure 18. Response of the bistable beam without SMA wires actuating. Phase space (red lines) and Poincare section (black points). (1) 100 Hz ((a) 940 N. (b) 800 N. (c) 640 N. (d) 300 N.). (2) 300 N. (e) 300 Hz. (f) 400 Hz. (g) 660 Hz. (h) 760 Hz. (i) 1000 Hz.).

Figure 19 shows the dynamic behavior of the bistable beam with the fully activated SMA wires (90°), as once the SMA wires be activated, the property of the system will be changed. With the activated SMA wires, the system can achieve the bistable behaviour readily as shown in Fig. 19, which is under the same situations with Fig. 18. Compared with the system responses generated with or without SMA wires actuation, it was found that the influence given by the excitation force amplitude can be reduced. Fig. 19 (b) shows that the chaotic response can be controlled by the SMA wires, and it becomes a quasi-periodic response compared with Fig. 18 (b). However, for different frequency excitation, the force contribution from the SMA wires is not enough to completely determine the system dynamic behaviour. It is noticeable that in the last case (i) the characteristic of the system is changed considerably, both two stable equilibria are disappeared, and the structure only can vibrate around the zero point.

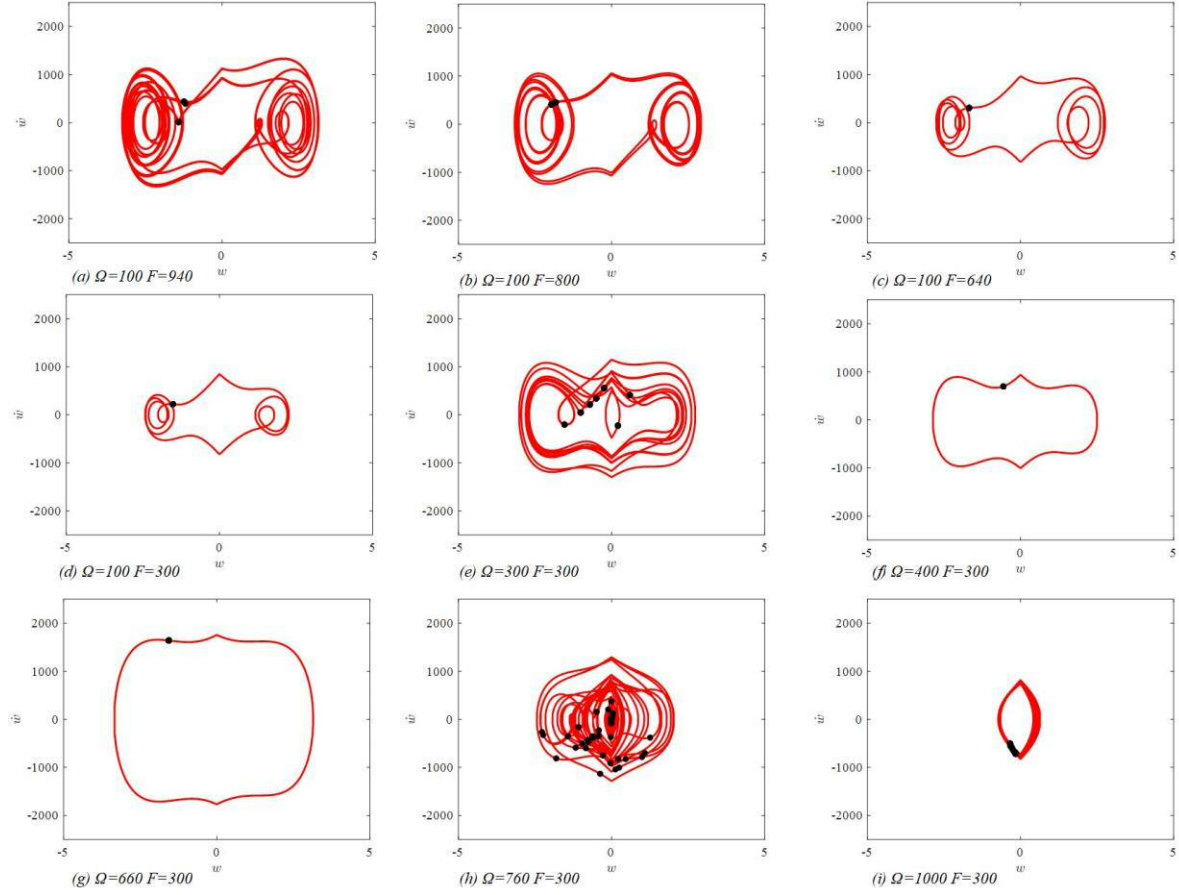


Figure 19. Response of the bistable beam with SMA wires actuating. Phase space (red lines) and Poincare section (black points). (1) 100 Hz ((a) 940 N. (b) 800 N. (c) 640 N. (d) 300 N.). (2) 300 N. (e) 300 Hz. (f) 400 Hz. (g) 660 Hz. (h) 760 Hz. (i) 1000 Hz.).

5. Conclusion

In this paper, a representative spring-mass model of a SMA wires actuated bistable beam was developed, tested and successfully demonstrated that the stable configurations of the structure can be actively switched. A single-DOF lumped model is formed by springs and mass to show different characteristics of the bistable system by selecting the corresponding parameters. Moreover, the thermomechanical behaviour of the SMA wires is investigated to build a constitutive relation for actuating the structure, and an experimental validation has been done to show a good agreement with the numerical simulation. An updated model is then developed to investigate the dynamic characteristics of SMA wires actuated bistable beam. Numerical simulations are carried out to show the response under different external excitation situations. It was found that the different excitations (amplitude and frequency) can lead to diverse dynamic behaviours of the bistable system, including both periodic response and chaotic. However, the thermomechanical loadings produced by the SMA wires can benefit for adjusting these dynamic behaviours. Although the thermomechanical loadings can also produce complex responses including chaos, the possibility of using SMA wires to prevent the chaos happening is shown in some

situations. The rich responses related to different excitations which may be caused by the potential external disturbances are analysed.

The developed bistable structures jointed with the SMA wires are capable to produce a larger deformation and a larger force, which is useful in many engineering applications, especially in small, lightweight mechanism and structures. The performance of the structures can be satisfactorily predicted and the dynamical characteristic can be easily performed when the proposed simplified model is applied. Moreover, because of the cooperation of the structure and SMA wires, the SMA wire significantly affects the stability of the structure, which renders the possibility to suppress the instability of structures under specific external excitations. The limitations of such bistable structures for proper functioning can therefore be effectively broken through. The results presented in this work provide a deep understanding of physical phenomena of this type of bistable devices.

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Compliance with ethical standards

Conflicts of interest The authors declared that they have no conflict of interest.

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